THE APOLLO PARACHUTE LANDING SYSTEM

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This Paper summarizes the work of a dedicated group of personnel from NASA MSC, North American Rockwell and Northrop Ventura.

INTRODUCTION

The "Apollo Parachute Landing System" today is probabily the most advanced, most thoroughly engineered and most thoroughly tested parachute system in existence. It stabilizes and decelerates the Apollo command module after the mission is completed to a descent velocity suitable for water landing. In addition it provides, together with the Launch Escape System, the means for safely landing the Apollo crew for all mission abort cases prior to obtaining orbit. The Apollo parachute system does not establish any records in recovered weight, velocity, or altitude of parachute deployment. However, the unique systems engineering approach and the extensive utilization of reliability and systems analysis combined with advanced design and testing methods have created an outstanding redundant man-rated system capable of safely landing the Apollo crew from pre-lift-off to completed missions.

The system approach started with a design concept that defined all landings including normal landing after completed mission and mission abort landings as operational cases and established the ground rule that no single component failure should cause loss of crew or mission failure. This somewhat arbitrary approach was replaced, as the development of the parachute system progressed, with a probability approach to the most or least likeable combinations of parallel or series functions and failures of components and subsystems. It ruled out those cases that had an extremely low probability of occurrence and required development and testing of those combinations with a probability of occurrence above a "significant" level related to total mission reliability. This method provided a clearly defined system reliability approach, and permitted the establishment of logical design criteria. The resulting parachute system was able to cope with the considerable command module weight increases caused by normal design changes and the added safety measures dictated by the command module fire. Landing after completed lunar mission is primarily a problem of reliability but not of high performance requirements. All limit design cases of high dynamic pressures, large command module oscillations and high loads are the result of abort cases, in particular, high altitude abort and pad abort.

The Apollo spacecraft and the subsystems involved in parachute landings are shown in Figure 1 and include the Apollo Command Module (CM), the Launch Escape System (LES) with canards and pitch-over control motors (PCM), the boost protection cover (BTC), and the apex cover or forward heat shield. The latter protects the parachute system located outside the crew compartment in the upper part of the command module around the LEM adapter docking tunnel.

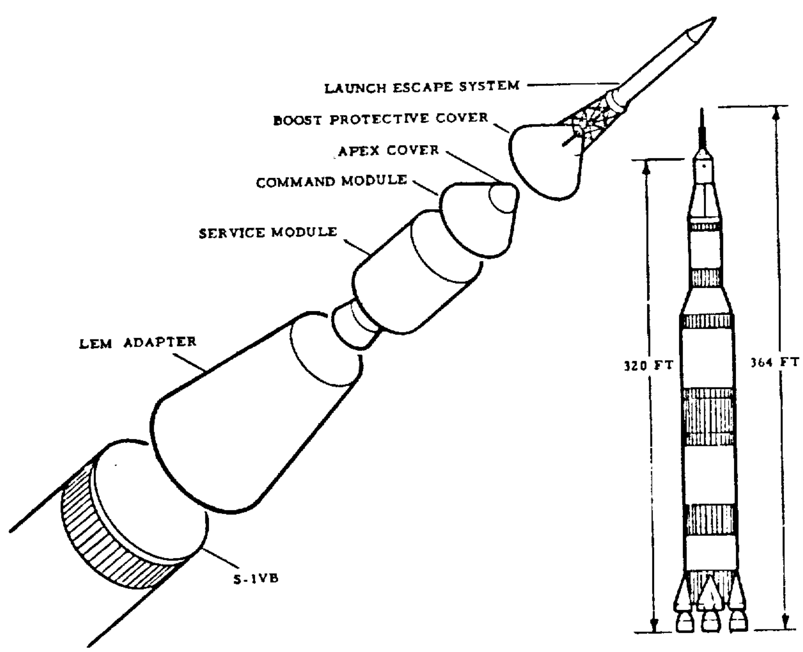

Figure 1. The Apollo Spacecraft

The subsequent paragraphs of this report discuss recovery modes, the approach to systems reliability, design criterias based on failure probability, new approaches to testing of the parachute system, series and parallel redundancy of vital components, and other interesting design details.

RECOVERY CONCEPT

The parachute landing system must assure safe landing for two primary landing modes: (a) landing after completed mission; and (b) landings by means of the launch escape system (LES) from the time the Apollo crew is in the spacecraft prior to take-off to approximately 300, 000 feet after second stage booster ignition. Above 300, 000 feet normal landings can be performed by the Apollo Command and Service Module (CSM) without the launch escape system.

Landings after mission abort involve special problems dependent upon the altitude at which abort takes place: (a) Pad-Abort causes extensive three axis spacecraft motions at parachute deployment and poses stringent minimum altitude requirements; (b) medium altitude abort involves complex sequencing modes; and (c) high altitude abort results in maximum dynamic pressures and parachute loads.

The selected emergency escape concept is similar to the Mercury spacecraft emergency landing system. It consists of a launch escape system (LES) that provides the command module with safe vertical and horizontal separation from the booster or the booster-fireball and assures sufficient altitude for proper, sequential parachute deployment. The size of the fireball, in case of an on-the-pad-emergency eliminates the ejection seat approach used on the Gemini spacecraft.

Early in the program, it was decided to establish the same reliability requirements for normal and abort mission landings. This creates the need of sufficient time for failure sensing and for obtaining adequate altitude for the deployment of a back-up parachute system in case of a malfunctioning primary system. The latter is especially difficult when one considers the necessary thrust and time required to cope with a booster tilt-over pad-abort emergency.

It may be of interest to mention here that only four man-rated systems exist which use the parachute as the primary means of transportation. These are, besides the Apollo spacecraft, the parachute systems for the Mercury and Gemini spacecrafts and the paratrooper parachute. All of these systems use the primary and back-up parachute concept.

PARACHUTE SYSTEM

The final parachute system selected for the Apollo command module is shown in Figure 2. Two ribbon drogue parachutes accomplish initial deceleration and stabilization, with only one parachute being required and the second parachute providing the back-up mode. Deploying both parachutes simultaneously eliminates the need for an emergency sensor, provides for faster CM stabilization and creates more favorable main parachute deployment conditions. After disconnect the two drogue parachutes are followed by three pilot parachute deployed Ringsail main parachutes; two of which will provide the rate of descent necessary for water landing. A detailed analysis of the probability of two simultaneous main parachute failures eliminated the necessity for a fourth main parachute. Again deploying all three parachutes precludes the need for a failure sensor, saves time and altitude and establishes more favorable landing conditions.

The selection of the particular parachutes is based on general performance characteristics as well as on the successful use of these parachute types for the Gemini and Mercury parachute landing systems.

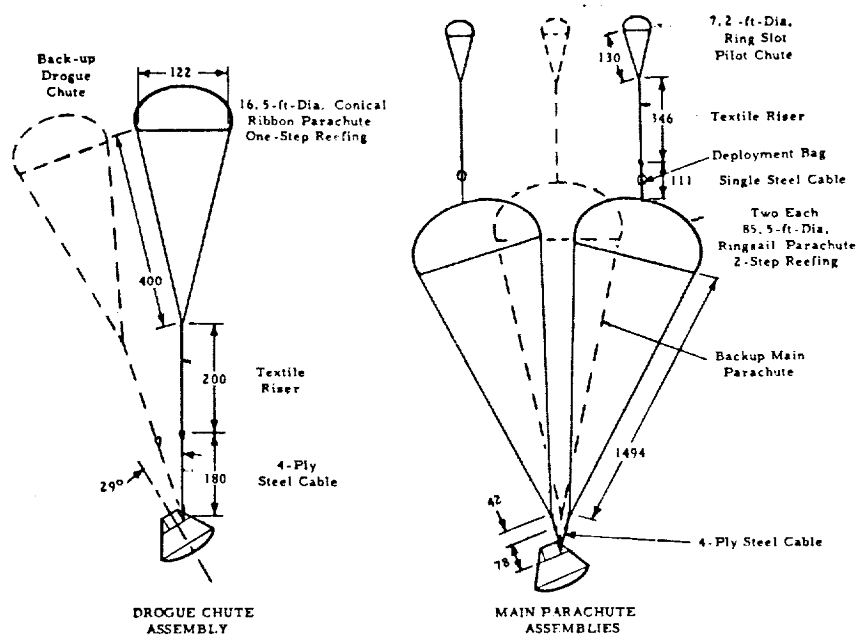

Figure 2. The Apollo Parachute System

NORMAL PARACHUTE DEPLOYMENT

The parachute deployment sequence for landing after completed mission is shown in Figure 3. The recovery sequence starts with the turning off of the reaction control system and with the ejection of the apex cover at an altitude of 25,000 feet. A 7.2 foot diameter ringslot parachute is used to support apex cover removal and to prevent recontact between cover and command module. The two drogue parachutes are mortar ejected, the individual attach points provide for a command module hang angle of 29.5 degrees. At 10,000 feet the drogue parachutes are disconnected by ordnance cutters and three pilot parachutes are mortar deployed simultaneously at 90 degrees to the command module vertical; these pilot parachutes in turn extract the three main parachutes. The deployment sequence is controlled by a fully automatic redundant sequencing system with a manual override mode available as back-up system at the astronauts discretion.

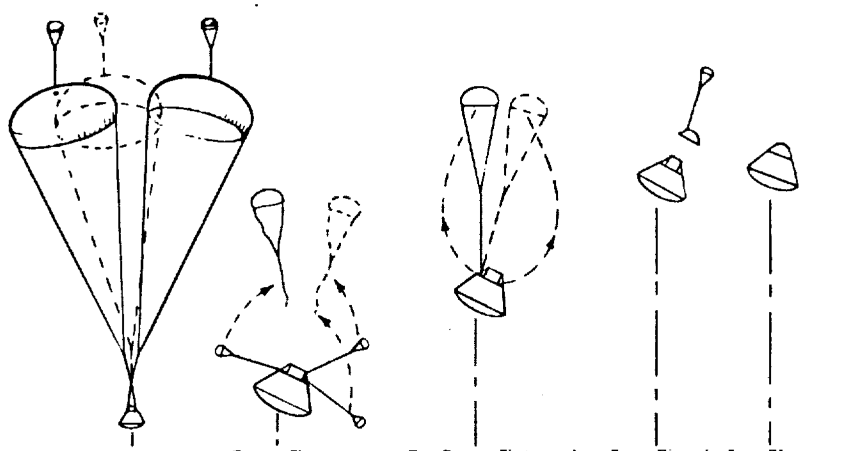

Figure 3. Normal Landing Sequence

ABORT PARACHUTE DEPLOYMENT SEQUENCE

The abort parachute deployment sequences are illustrated in Figure 4. This mode is operational from prior to launch to an altitude of approximately 300,000 feet. Upon abort command the launch escape motor fires and lifts the CM off the Saturn booster. The pitch over motor and the canards provide horizontal separation, CM turn-around, and a limited degree of stability. Fourteen seconds after CM lift-off, the escape tower, boost protection cover, and docking probe separate followed by the time or altitude controlled parachute deployment sequence depending on the altitude of recovery initiation. The primary control again is provided by the automatic redundant sequencing system with an astronaut controlled override mode available as back-up. The astronaut, on pad or low altitude abort, can select to override the drogue parachutes and to deploy the main parachutes immediately as long as the dynamic pressure and the altitude are within the allowable main parachute deployment limits.

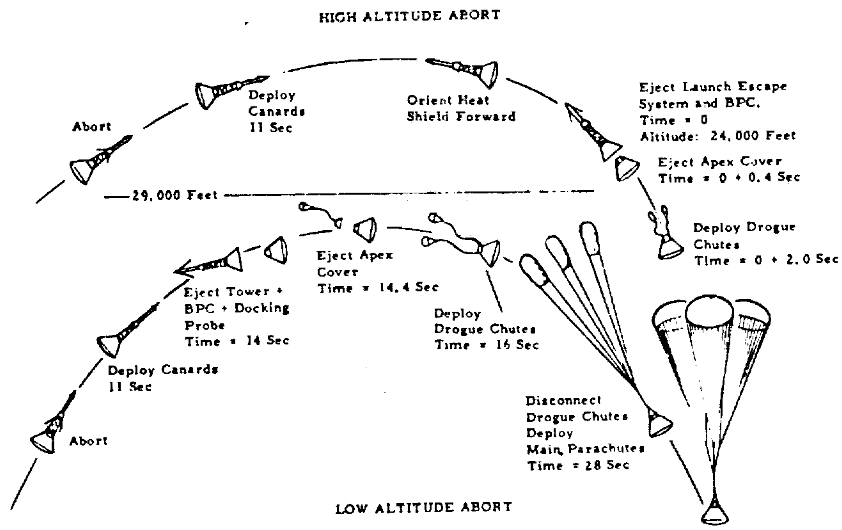

Figure 4. Abort Landing Sequences

PARACHUTE DEPLOYMENT ENVELOPE

The operational parachute deployment envelope defines the two primary regions of drogue parachute and main parachute deployment, see Figure 5. At the final phase of a completed mission the command module after reentry, descends in stable attitude. At an altitude of approximately 25,000 feet and below 124 psf an automatic sequencing system deploys the two drogue parachutes (normal reentry region in Figure 5). The astronaut may deploy the drogue parachutes up to 40,000 feet altitude if flight conditions make it advisable to do so.

In case of high altitude abort command module motions can result in dynamic pressures as high as 204 psf; this precludes manual deployment of the drogue parachutes above 25,000 feet. Pad abort and low or medium altitude abort require parachute deployment at altitudes as low as 3,000 feet at dynamic pressures in the 10 to 100 psf range.

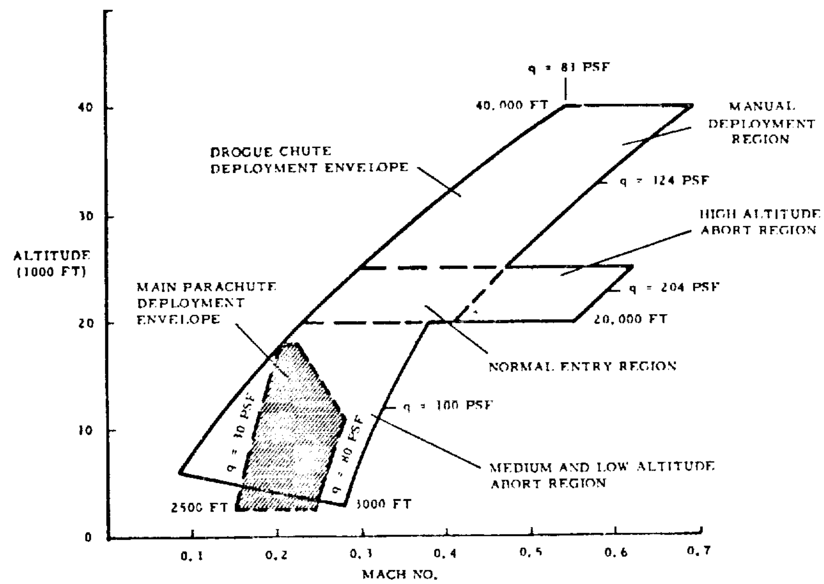

Figure 5. Parachute Deployment Envelope

The main parachute deployment region is defined by the cross-hatched area in Figure 5. Automatic simultaneous disconnect of the two drogue parachutes and deployment of the three main parachutes by means of mortar ejected pilot parachutes occurs at 11,000 feet. Main parachute deployment by automatic control may occur in abort cases between 10,000 to 18,000 feet due to aneroid sensor lag and ascent and descent hysteresis.

It is interesting to note that during the interval from drogue parachute disconnect to main parachute canopy stretch a dynamic pressure increase of 20 psf can occur in vertical descent.

The command module during reentry is stabilized by a redundant reaction control system (RCS). Use of a chemically active fuel prevents use of the RCS after parachute deployment. Lack of RCS stabilization during abort causes command module motions in pitch, roll and yaw. This complicates parachute deployment, causes nonsynchronous main parachute deployment and opening, and increases individual parachute loads. All these conditions were considered in determining parachute deployment and load condition.

SYSTEM APPROACH

A qualitative system analysis at the start of the Apollo program defined a parachute system consisting of one drogue parachute and two main parachutes as the primary system for successful normal landing. A second drogue parachute and a third main parachute, formed a back-up reserve that permitted failure of one drogue and/or one main parachute without loss of crew or command modules. Potential single point failures within the recovery system were to be avoided to the maximum possible extent. A minimum factor of safety of 1.35 was defined for all components and parachute stages.

This design rule concept was supplemented as the project progressed by a statistical approach to the probability of occurrences of single and multiple parallel and series failures. An extensive reliability analysis was performed that included mission abort, sequencing failures, parachute and component failures, command module attitude and motions at parachute deployment, pyro-mechanical failures due to premature action as well as due to lag of action, aerodynamic interference between parachutes, etc. This system reliability assessment utilized a computerized mathematical model that included sensitivity studies, calculations of the reliability contributed by all components and subassemblies to the system and a reliability apportionment for the parachute subsystem.

A flight mode probability analysis concluded that cases where a system failure occurred with less than a "significant" probability need not be considered as a design case. This probability analysis was applied in a logical fashion by looking at each component, subassembly, and subsystem and considering:

What is its failure mode?
Its probability of failure?
Its test history?

Its complexity?

Can it be inspected and checked?

Can its failure or impending failure be detected?

Is it active (relay, ordnance, etc.) or passive (structure)?

Table 1 shows a typical probability analysis for actual flight modes of which 12 different modes were investigated. Similar approaches were used to analyze various parachute cluster deployment modes shown in Figure 6. The superiority of a parachute cluster with independently deployed parachutes (system I) in comparison to the more conventional deployment approaches, systems II and III, is obvious.

Table 1. Probability of Parachute Load and Failure Occurrence

Flight Mode	No. of Parachutes	Main Parachute Loads: 1. Stage Reefed	2. Stage Reefed	Disreef	Maximum Total Load	Probability of Occurrence	Design Case	Comment
(1) 1	(2) OD 2M	(3) > 23,000	> 23,000	> 23,000	(4) > 40,000	Below significant	No	
1	OD 3M	> 23,000	> 23,000	< 23,000	> 40,000	Below significant	No	
1	1D 2M	> 23,000	< 23,000	< 23,000	≃ 40,000	Above significant	Yes	Total load is marginal
1	1D 3M	< 23,000	< 23,000	< 23,000	< 40,000	Above significant	Yes	
1	2D 2M	< 23,000	< 23,000	< 23,000	< 40,000	Above significant	Yes	
1	2D 3M	< 23,000	< 23,000	< 23,000	< 40,000	Above significant	Yes	
2	---	---	---	---				
3	---	---	---	---				
4	---	---	---	---				
5	---	---	---	---				

(1) Flight Mode 1: High altitude abort, maximum dynamic pressure q, drogue disconnect and main parachute deployment at unfavorable CM attitude and motion. 12 Flight modes considered.

(2) Stands for no drogue chute, 2 main parachutes

(3) Assumed maximum allowable parachute load

(4) Assumed maximum allowable cluster load

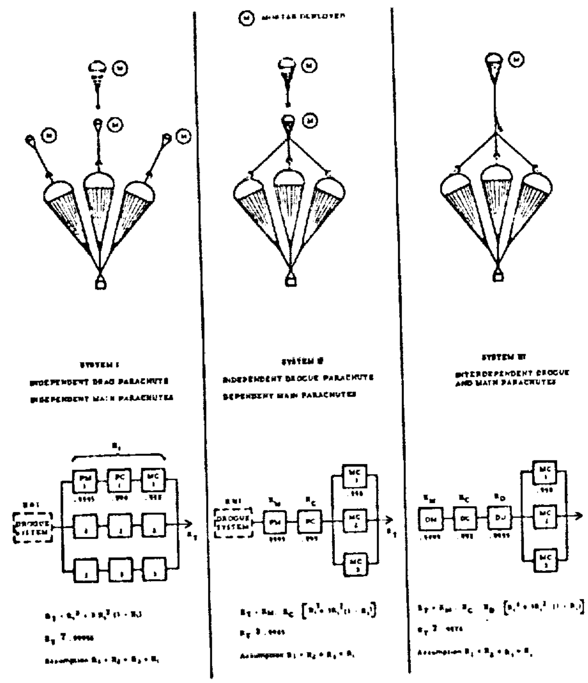

Figure 6. Reliability Comparison of Parachute Cluster Systems

DESIGN CRITERIA

The results of this probability analysis were then used to establish ground rules and design criteria with each case jointly agreed upon with the prime contractor North American Rockwell Corporation and NASA MSC, the responsible Government agency. Following design rules and criteria are being applied:

1) All mission aborts are operational modes.

2) The primary system consists of a single drogue parachute and two main parachutes with a redundant drogue parachute and a redundant main parachute serving as back-up.

3) No single component failure shall cause loss of crew or mission.

4) The probability of occurrence of parallel failures such as loss of two drogue parachutes shall be minimized to the maximum extent possible. Failures such as loss of one drogue parachute and one main parachute are to be considered.

5) The total parachute landing system reliability must be equal to or better than 0.99994.

6) Components or assemblies that control active functions such as ordnance devices, aneroids or relays must be designed for prevention of premature functioning as well as nonfunctioning.

7) A minimum factor of safety of 1.35 must be proven for all structural components and parachute load stages in ultimate load tests.

8) All parachutes shall be independently deployed and shall utilize active deployment means.

DESIGN LOADS

An analysis of the parachute deployment envelope and of the design criteria indicates that the maximum drogue parachute and main parachute design loads do not occur at normal reentry but at abort conditions combined with other failure modes.

The probability analysis described previously determined that following combinations, of events, component failures and anomalies produced the maximum drogue parachute design loads:

High altitude abort

One drogue parachute

Unfavorable command module attitude and motions at drogue parachute deployment.

The maximum main parachute design loads are produced by following combinations:

High altitude abort

Single drogue parachute

Two main parachutes

Differential main parachute deployment due to unfavorable CM attitude at parachute extraction

Maximum differential reefing cutter time

Aerodynamic blanketing between reefed parachutes resulting in a lag and lead parachute condition.

These combinations not only affect the reefed parachute load but all subsequent load stages as well. The maximum loads of the reefed drogue and main parachutes are not caused by the same combination of events; this necessitates an extensive analysis and mutual agreements among all agencies involved. It may be mentioned here that as soon as command module motions in three axes become important a six-degree-of-freedom computer program is desirable for determining maximum design loads. Figure 7 shows the calculated parachute loads occurring at normal reentry, the maximum calculated "design loads" based on a combination of unfavorable events and the ultimate load calculated to be 1.35 times the design load.

A requirement, new in parachute development, is the need for proving in tests that all parachute stages will withstand the ultimate load of 1.35 times the design load.

Actual ultimate load test points are shown in Figure 7 to document compliance with the stringent test requirements.

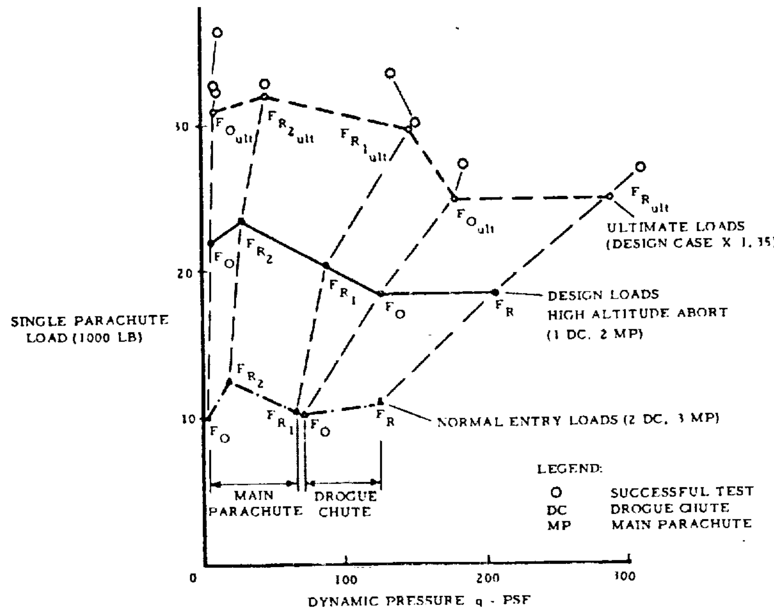

Figure 7. Drogue Parachute and Main Parachute Loads

DEVELOPMENT AND QUALIFICATION TESTS

Testing of the Apollo parachute system introduces problems not normally encountered in testing of parachute systems. The design limit loads for both the drogue parachute and the main parachute are calculated values that cannot be obtained in aircraft drop tests with a free falling Apollo command module test vehicle. Instrumented cylindrical test vehicles (ICTV) and a parachute test vehicle (PTV) that duplicated the Apollo CM parachute deck but had a much smaller vehicle diameter were substituted. These test vehicles besides being more economical were able to reach after aircraft drop velocities in vertical descent that permitted to obtain the design as well as ultimate parachute loads.

Test procedures were greatly complicated by the requirements that all components and parachute stages had to demonstrate a minimum factor of safety of 1.35 in vertical tests and that component failures had to be duplicated in tests.

Final qualification tests were conducted with spacecraft end item hardware and a geometrically and dynamically similar Apollo boilerplate test vehicle. Important operational modes and specific points of the parachute deployment envelope, see Figure 5, were selected as test conditions.

ICTV's and PTV's were dropped from B-52 and B-66 aircraft, a modified C-133 aircraft was used for dropping the boilerplate test vehicles. Single and multiple programmer parachutes established vertical trajectories and test conditions for individual parachute tests or consecutive tests of drogue and main parachutes at the same test mission. An Apollo boilerplate parachute test vehicle prior to and after test is shown in Figures 8 and 9.

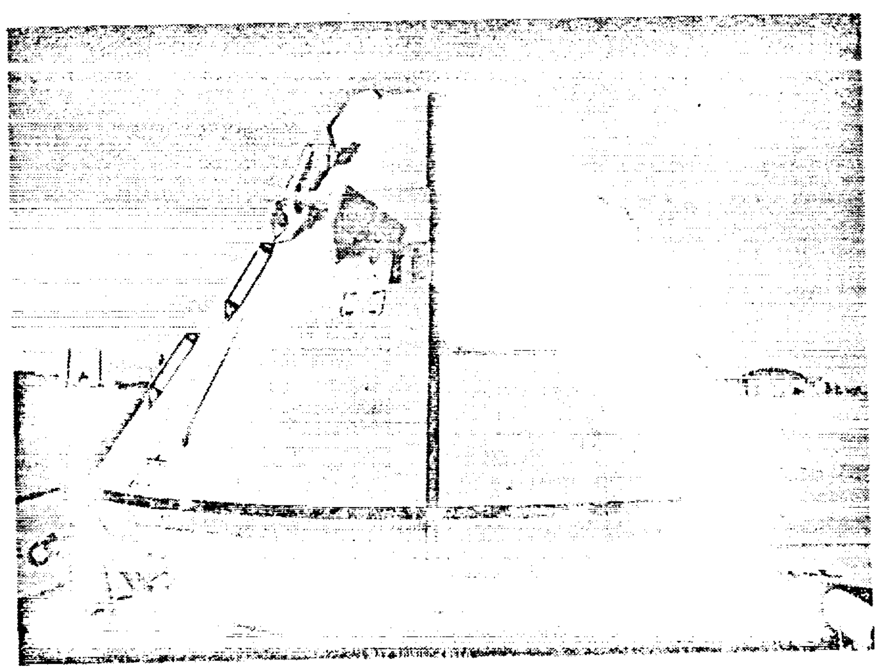

Figure 8. Apollo Boilerplate Vehicle Ready for Test

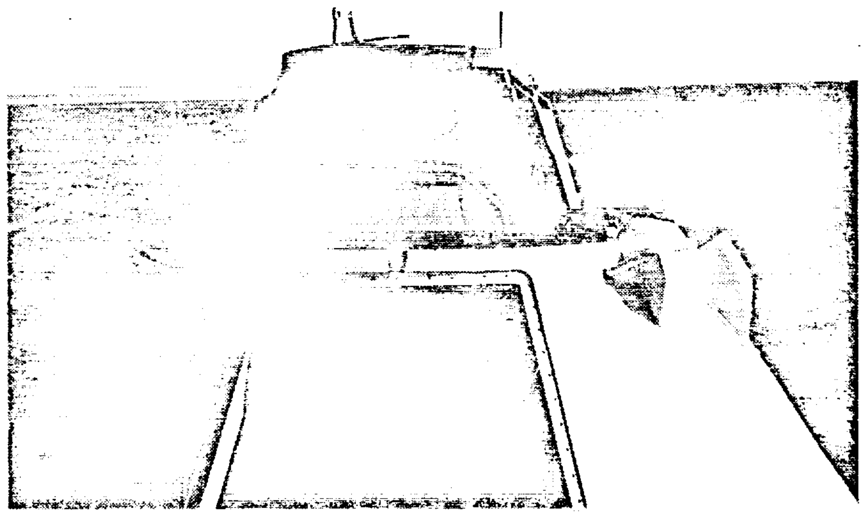

Figure 9. Apollo Boilerplate Vehicle After Test

PARACHUTE LOAD TESTS

Design load and ultimate load tests were conducted with single and multiple drogue parachutes and main parachutes using ICTV's and PTV test vehicles. Ultimate loads of the first reefed parachute stage can be obtained by parachute deployment at a high dynamic pressure. This approach fails to produce ultimate loads in subsequent reefed stages since the dynamic pressure at the end of the first reefing stage always approaches the same value independent of the starting point. This problem was solved by increasing the weight of the test vehicle, by decreasing the length of the reefing.time or by a combination of both methods.

It was found during these tests that the wake of the test vehicle had a pronounced effect not only on the drag area of the drogue parachute in the wake of the forebody but surprisingly also on the dynamic load factor C_K. This is indicated by the data in Figure 10 which shows for various test vehicles the drogue parachute drag areas, the dynamic load factor C_K and typical parachute force traces. The turbulent wake not only decreases the drag area but increases notably the load fluctuations and thus the dynamic load factor. These data have to be taken into account in order to predict what loads obtained behind an ICTV or PTV are equivalent to load predictions for the command module.

It was impossible to predict parachute test loads with the desired accuracy of 5 percent. This requires not only proper load prediction methods but also proper test conditions through programmer parachutes and time delays, accurate on-board instrumentation measurements, and accurate meteorological and range instrumentation data that can be coordinated with the on-board telemetry measurements. It was found that the technology of parachute testing requires notable improvements before test data can be predicted, obtained, and evaluated with an accuracy approaching 5 percent.

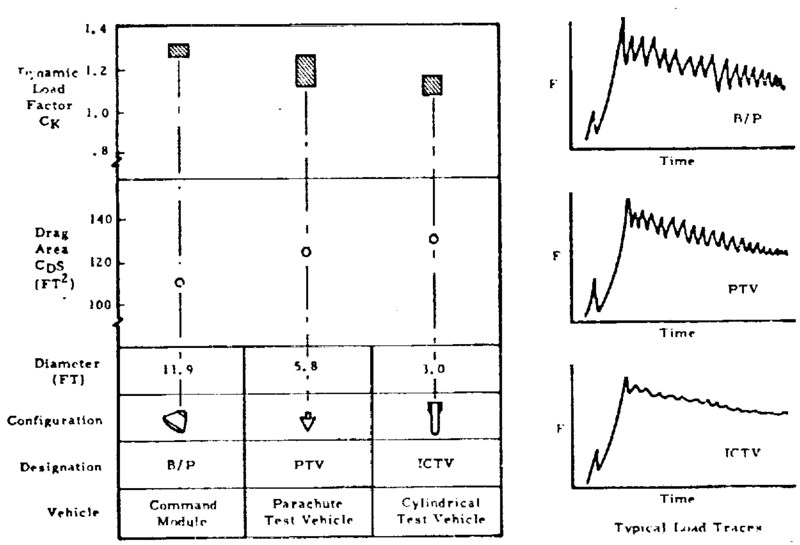

Figure 10. Drogue Parachute Drag Area $C_D \cdot S$ and Dynamic Load Factor C_K for Various Forebodies

FAILURE TEST

Component failures that were duplicated in tests included single and series drogue parachute and main parachute failures, main parachute second stage reefing failures as well as other combinations. All these tests were monitored by a reliability engineering group in order to assure maximum benefits as well as independent assessment of test success or failure.

ENVIRONMENTAL TEST

Extensive tests were performed to determine if space environment, primarily high vacuum, and high temperature or vacuum-temperature cycling would affect nylon, dacron, elastomers, pyrotechnics and metals. No strength degradation was encountered on nylon and dacron when exposed to a vacuum of 10^{-6} Torr, the vacuum specified for the Apollo parachute system. Detailed temperature profiles were established for the drogue and main parachutes for spaceflight as well as for reentry with follow-on normal landings. It was found that the main parachute temperature increased to 140F^{o} after apex cover ejection from the hot air flowing around the heat shield and streaming along the packed main parachutes. The resultant strength loss of 4 to 7 percent cannot be neglected when working with a factor of safety of 1.35. A strength degrading factor was introduced in ultimate load tests in the form of an equivalent higher test load. The results of the extensive laboratory environmental tests are documented in numerous test reports.

QUALIFICATION TESTS

Seven qualification drop tests were conducted with the Apollo boilerplate test vehicle and the spacecraft end item parachute system. This included three normal reentry tests with variation in drogue parachute deployment altitude and use of either two or one drogue parachute, the latter mode duplicating a single parachute failure. Two tests duplicated high altitude aborts, giving the maximum dynamic pressure at parachute deployment. Only one drogue parachute was used in these tests in order to obtain representative high main parachute loads. Two tests covered low altitude aborts using in one test, two drogue parachutes with minimum time sequence for drogue parachute and main parachute deployment. The second test duplicated an astronaut initiated drogue parachute override with immediate main parachute deployment, a condition that resulted in a higher than limit case dynamic pressure at main parachute opening. The two low altitude abort tests duplicated deployment in a near horizontal trajectory with representative CM attitudes and motions. All qualification tests were successful. Attempts to obtain good parachute load data in qualification tests without introducing non-spacecraft type load links was not entirely successful due to the difficulty of instrumenting actual S/C hardware.

PARACHUTE SYSTEM DETAILS

Numerous interesting design details are contained in the Apollo parachute system. The reliability requirement of independent parachute deployment, coupled with large command module oscillations, necessitates divergent drogue parachute and main pilot parachute deployment angles coupled with positive thruster type deployment. The command module oscillations create the possibility of contact between the parachute risers and the hot rear heat shield, and last but not least, the increase in CM weight without an accompanying increase in compartment volume or allowable parachute cluster loads resulted in novel design approaches for parachute packing, storage and shape retention.

DROGUE PARACHUTE MORTAR ASSEMBLY

The installation of the two drogue parachute mortars in one of the four parachute compartment bays is shown in Figure 11. All drogue parachute and main parachute risers end in steel cables which are attached to the CM by means of the so-called "flower pot." As mentioned previously, steel cables were selected to avoid riser damage due to contact with the hot heat shield in case of command module oscillations. The need for small steel cable bending radii was solved by using four ply steel cables swagged into common fittings for both the drogue and the main parachute risers. The white strings shown in Figure 11 are electrical leads to strain gages attached to the risers and are not part of spacecraft equipment.

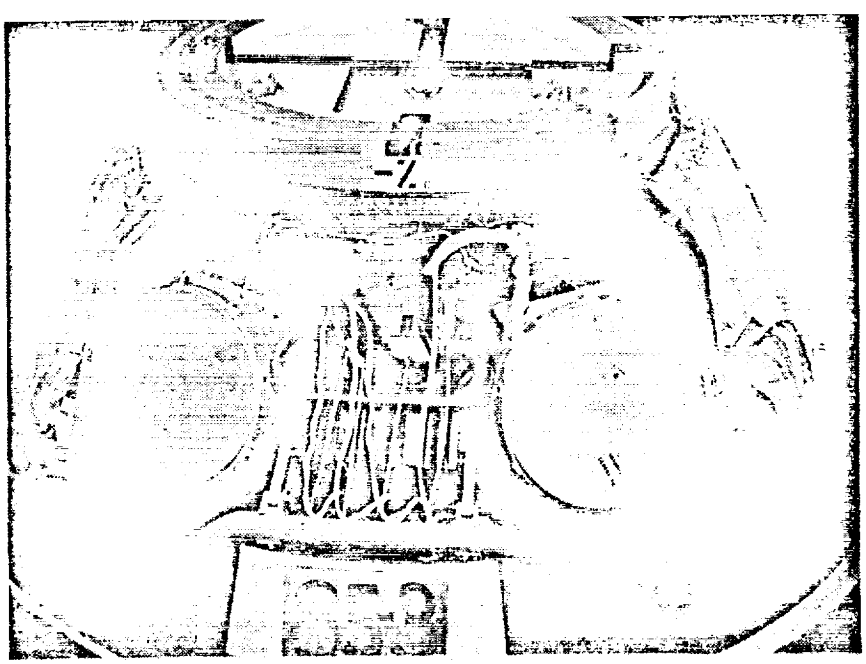

Figure 11. Drogue Parachute Bay

Figure 12 shows the mortar assembly which incorporates an unusual steel cable storage and cartridge orifice design. In order to prevent riser kinking both riser ends are secured and the risers are coiled under tension without twisting the ends; the risers are then cast in urethane foam. Upon deployment the light foam disintegrates and the risers stretch without kinking by releasing the pre-wound tension.

Command module motions during drogue parachute deployment may cause the steel risers to bend and roll over the flower pot resulting in abrasion between the Titanium flower pot collar and the steel cables. Surrounding each individual steel cable with lead tubing helped to minimize this problem; see Figure 13. All mortars are hermetically sealed and dual cartridges requiring symptomatic firing are used.

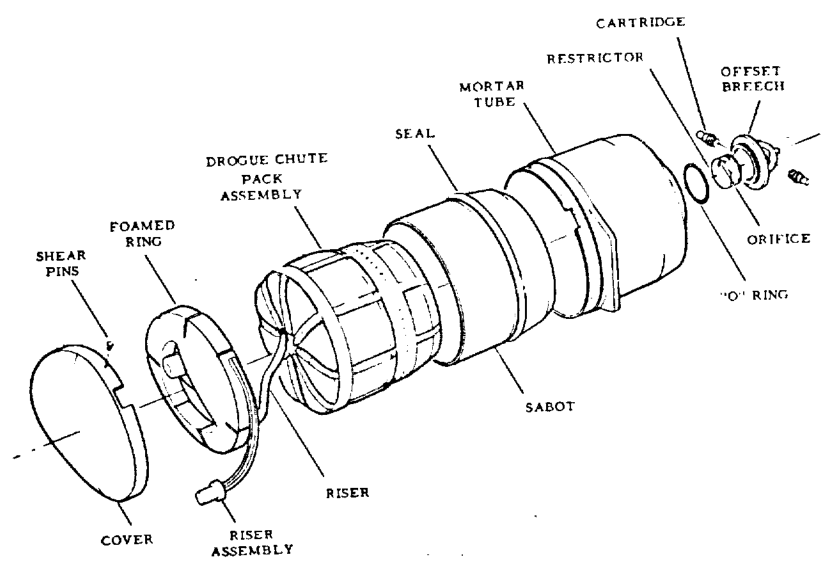

Figure 12. Drogue Parachute Mortar Assembly

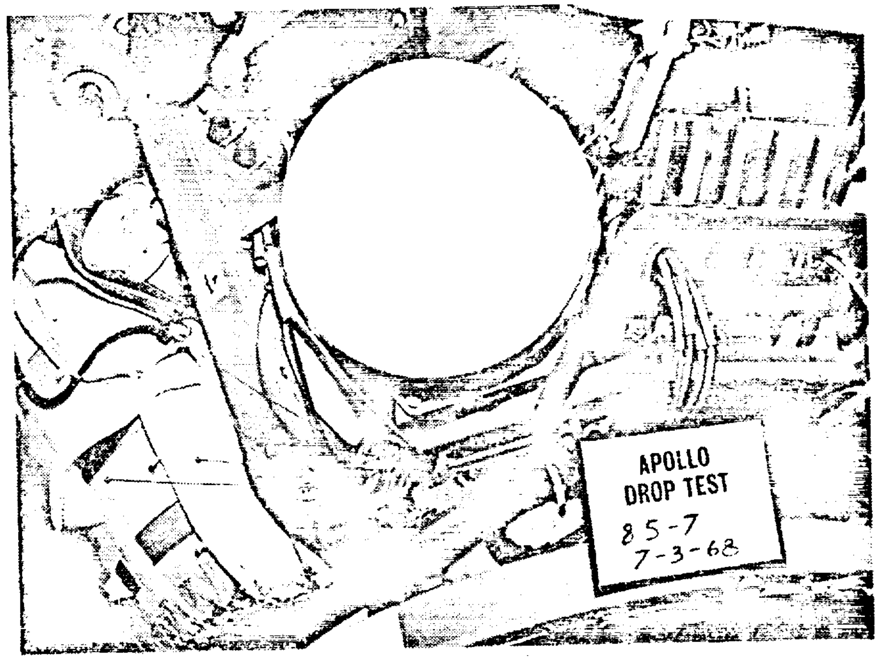

Figure 13. Steel Cable Protection

MORTAR ORIFICE DESIGN

The increase in CM weight and the resultant increase in drogue parachute size and weight produced reaction forces upon mortar firing that could not be tolerated by the CM structure. An eroding hybrid orifice was developed that maintained the required muzzle velocity for the heavier drogue parachutes without increasing the reaction loads of the more powerful cartridges. Designs of standard and hybrid orifices and pressure characteristics are compared in Figure 14. Previously used orifices as shown in the upper left hand corner of Figure 14 produce the typical pressure-time curve as seen in the right hand diagram. The eroding orifice has brass and aluminum inserts which burn away progressively and allow more gas to enter the mortar tube. The aluminum insert keeps the temperature level of the expanding gas high. This design results in a reasonably constant mortar tube pressure and maintains the mortar reaction loads within allowable limits.

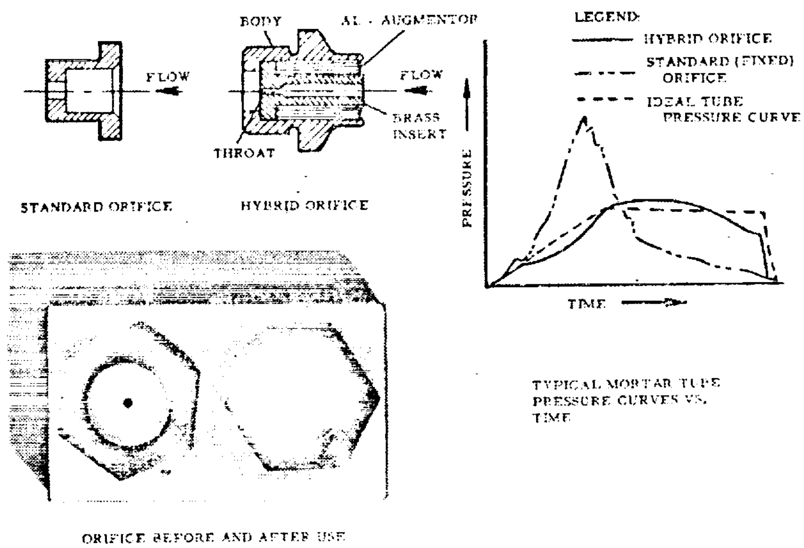

Figure 14. Mortar Orifice Details

MAIN PARACHUTE REEFING SYSTEM

Project Mercury was the first man-rated parachute system that used a reefed parachute. The increase in CM weight without an equivalent increase in allowable parachute loads made a two-stage reefing system mandatory for the three main parachutes. An additional complication was introduced by the requirement that the reefed main parachutes had to be protected against premature disreefing as well as against failure to disreef, a reliability requirement introduced for the first time on the Apollo drogue and main parachutes. The details of the resultant mechanical design of the main parachute reefing system are shown in Figure 15. Two reefing lines are used for the first stage, with each line having its individual set of two reefing cutters. Rupture or premature severance of one line will not disreef the parachute; separation of both lines is required to disreef the parachute to the second stage. The second stage has only one reefing line with two cutters. Analysis and tests have proven that premature rupture of the second stage reefing line will not result in destruction of the parachute.

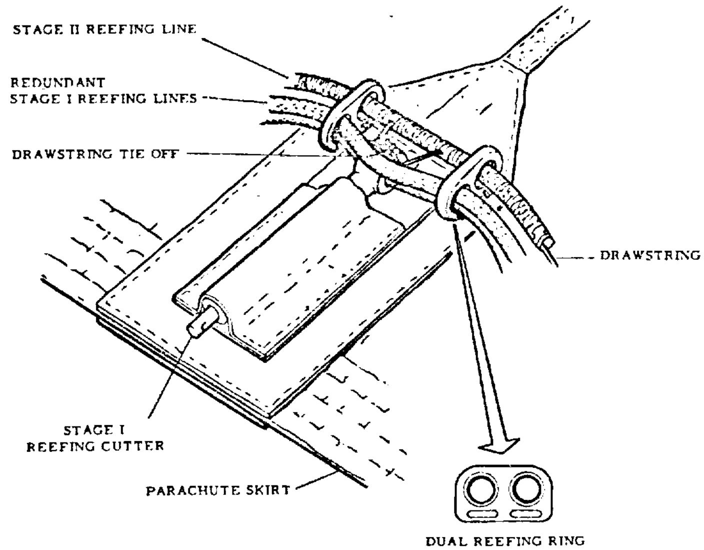

Figure 15. Main Parachute Reefing

Mid-gore reefing is used on all parachutes with the cutters attached to the canopy radials. Dual reefing rings, called "Siamese Rings" were developed with both first stage lines passing through the same ring opening. The slack part of the second stage reefing line is gathered with a draw string of the same length as the first stage line; this draw string approach avoids the problems of stowing and securing the second stage line. This reefing system worked without malfunction during all development and qualification tests.

MAIN PARACHUTE RETENTION SYSTEM

The main parachute deployment bags form part of a truncated cone segment and must maintain their highly compressed form throughout storage and mission in order to assure a specific gap between the apex cover and the packed parachute necessary for heat protection during and after reentry. During the development cycle the hard packed main parachutes experienced a 25 percent weight increase and a 6 percent decrease in allowable volume. This resulted in a parachute pack density of 0.0245 lb/cubic inch. The truncated cone form is maintained for a period of one year without growth by combined pressure and vacuum packing and storage of the bag in a wooden compartment former. Vacuum sealing is maintained with two layers of polyethylene film. The bags in the command module parachute bays are restrained with daisy chain retainers on three sides, see Figure 16. The retention system connects directly to the deployment bag without intermittent flaps. The deployment bag itself incorporates several layers of dacron felt for heat protection.

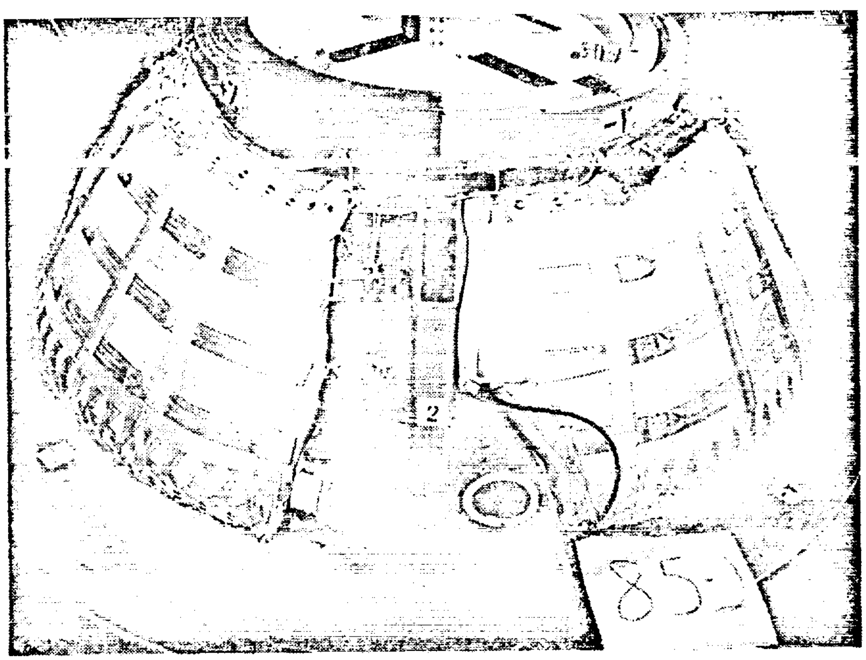

Figure 16. Main Parachute Retention System

The large presses required for packing of the main parachutes into the conical shaped bags are shown in Figure 17. The parachute, in vacuum storage in the wooden former sealed with plastic film, ready for transportation or storage is shown in Figure 18. This concept has proven its shape holding capability in several Apollo flights.

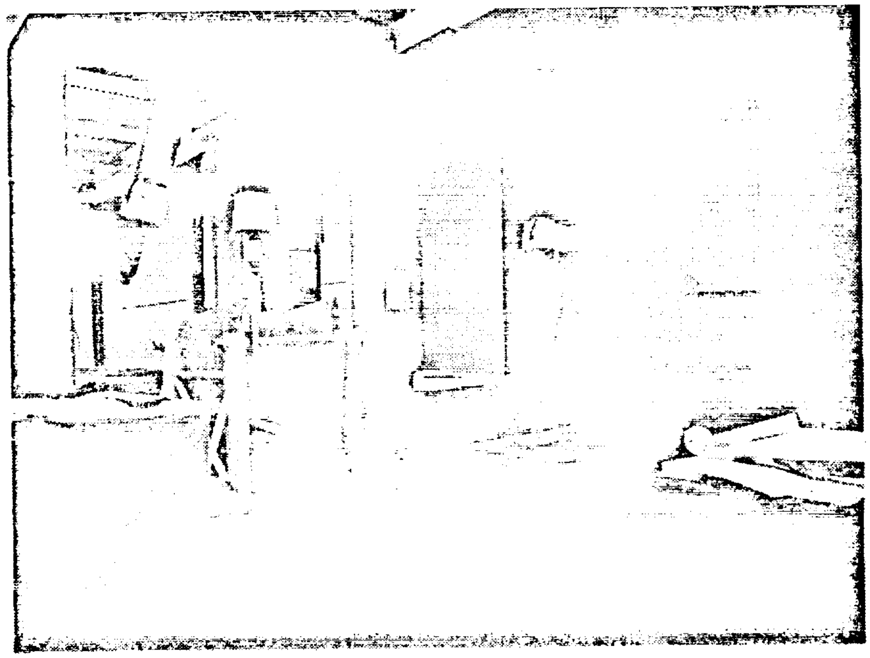

Figure 17. Parachute Packing Presses

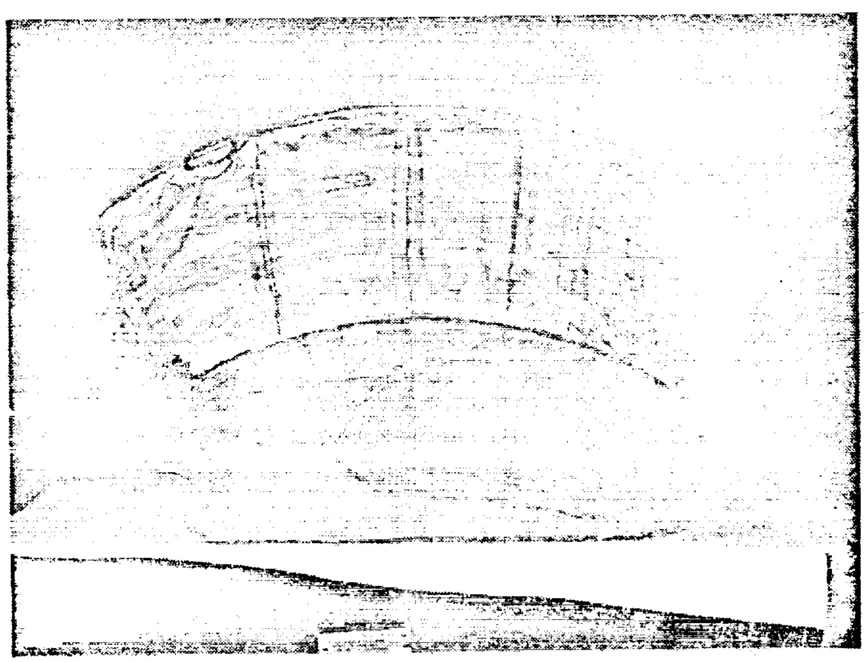

Figure 18. Main Parachute Vacuum Storage

CONCLUSIONS

The Apollo Parachute System is capable of safely landing the Apollo Command Module from time prior to take-off to completed space mission. The ability to cope with all conceivable emergencies, full system redundancy, minimum weight and volume, and a maximum parachute force equivalent to less than 3 g's are outstanding characteristics of the Apollo Parachute Landing System. The basic design proved flexible enough to accept a substantial increase in command module weight, and a resultant increase in recovery envelope and velocity of parachute deployment without changing parachute volume or load requirements. A systems and reliability engineering approach unprecedented in scope and complexity in parachute development required the joint engineering efforts and skills of NASA MSC, North American Rockwell and Northrop to meet performance and schedule requirements. A major difficulty in design and development was the lack of adequate analytical methods for properly predicting dynamic behavior, loads and stresses of the aerodynamic decelerators and the combined parachute systems. Development of these prediction methods must precede any major improvements in weight, volume, loads, or testing economy of future spacecraft landing systems.

This paper describes the complex requirements for the Apollo spacecraft landing system, the broad engineering spectrum and the outstanding reliability approach required for the development of this man-rated spacecraft parachute landing system.